Gazi University Journal of Science
GU J Sci
25(2):435-446 (2012)

ORIGINAL ARTICLE

Tracking Control Solution for Road Simulators: Model-based Iterative Learning Control Approach Improved by Time-domain Modelling

Ufuk DURSUN [1,♠], Timuçin BAYRAM[1]

[1]Bias Elek. Mek. Bilg. Müh. San. ve Dan. Tic. Ltd. Şti.“Test Systems Division by Bias”, İkitelli O.S.B Metal İş San. Sit. 4. Blok No:24 Başakşehir/İstanbul

Received:10.11.2011 Revised: 27.02.2012 Accepted:01.03.2012

ABSTRACT

Fatigue and durability tests are very important to develop and to optimize mechanical structure used in automotive, defence technology. Forces in application of a product developed or being developed are named as road data. After position, force and acceleration are collected during real world application, reproducing this data of measurements in laboratory brings with a complicated control problem, as another word, it is control research area. Nonlinear structure of hydraulic actuators and test specimen with changing model parameters and noises restricts tracking performance of standard control approaches. In this paper, to reproduce the road data, “Time domain Modal-based Iterative Learning Control “procedure is recommended. The control algorithm is applied on 2-poster test rig.

Key Words: *Test systems, road simulator, test rig, hydraulic control, iterative control*

1. INTRODUCTION

Fatigue and durability tests are important to develop or to optimize a product. Additionally, test systems are used to produce needed forces on test specimens. Road simulators, as a subsection of test systems, have ability of reproducing road data collected from a specimen during standard working. Road data could be acceleration, force or strain. Also, reproducing the real world data in laboratory bring with a trajectory tracking control problem. Figure 1 shows steps of the road simulation.

Test systems generally have hydraulic actuators. Hydraulic actuators and test specimens have nonlinear characteristic. On the other hand, deformation of test specimen and heating of the hydraulic oil cause in changing parameters of the test system. To summarize, related the test system’s characteristic, there is different kind of control approach to reproduce the road data, detailed explanation is in [1]. On the other hand, deformation of test specimen and heating of the hydraulic oil cause in changing parameters of the test system. To summarize, related the test system’s characteristic, there is different kind of control approach to reproduce the road data, detailed explanation is in [1].

[♠] Corresponding author, e-mail: udursun@bias.com.tr

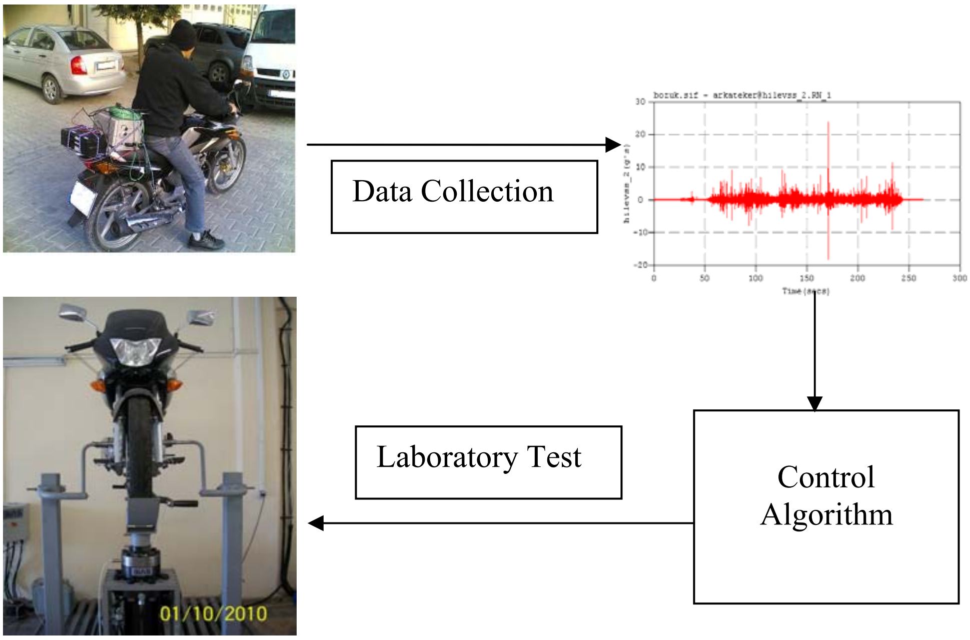

Figure 1. Steps of a road simulation.

Basically, PID control is still effective due to application [2, 3]. Road data consists of a wide range of frequency spectrum with random magnitudes. Trajectory tracking performance of PID control is theoretically and practically effective in a linear working area. On the other hand, usage feedback brings with adding noise, so that digital filter online usage reduces closed loop system performance. Especially, ICP and strain gage type sensors used generally in road simulators are very sensitive to noise.

Test systems are nonlinear and have changing parameters. Additionally, it is possible to design an adaptive controller to compensate effect of parameter changing of the system, different kind of adaptive controller explained in [4-9]. Adaptive control has relationship directly with mathematical model of the test system (with specimen). Unfortunately, test system should be universal, because test specimen could be changing.

Dynamic optimization to get optimal control parameters subjected to uncertainty and noise has good performance on road simulators as given in [10-14]. H_∞ or H_2 optimization norms are used to synthesis of the optimal dynamic performance in effective frequency range.

In order to get better performance in trajectory tracking Iterative Learning Control (ILC) is a "simple", universal and effective way as given in [15-21]. In literature, it seems that the combination of other control approaches and the ILC brings with universal and effective solution.

In this paper model-based iterative learning control is designed for road simulators and applied to a 2-poster. Mainly advantage of this paper that time domain system identification and inversion procedure is designed and applied. Similar working on Model-based ILC focus on frequency domain system identification, despite of the advantages of time domain modelling. [22] explained detailed advantages of time domain modelling. This paper provides time domain solution on model- based ILC and it is applied on 2-poster test rig.

2.DYNAMIC EQUATIONS AND ANALYSIS

In test systems, hydraulic actuators are frequently used because of high power capacity of hydraulic systems. In Figure 2, it seems symbolic road simulator test system, including a servo valve, hydraulic cylinder and quarter car model of vehicle.

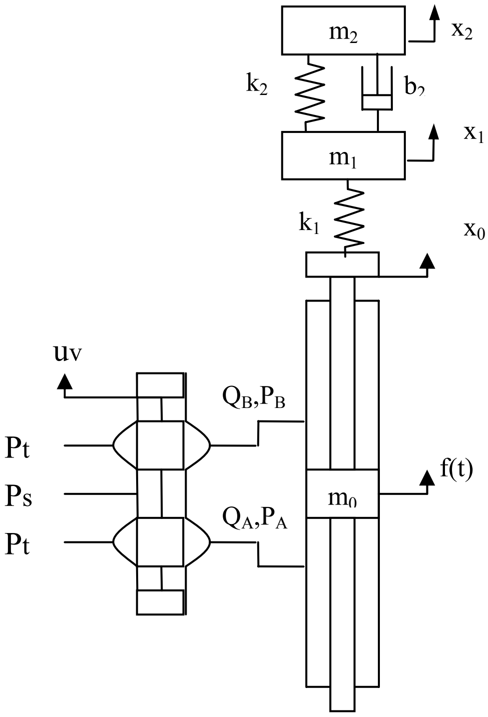

Figure 2. Symbolic road simulator.

Servo valve dynamic equation is constructed from orifice fluent equation, as given in [23, 24] and can be written as

$$Q_L = K_V.u_v.\sqrt{\Delta P} = K_V.u_v\sqrt{\frac{P_s - P_t - P_L}{2}} \quad , \qquad (1)$$

where Q_L is load flow, K_V is valve gain, u_v is spool position, P_s is supply pressure, P_t is tank pressure and P_L is load pressure. It is assumed that the actuator dynamic has necessary bandwidth. Cylinder dynamic equation is given in (2).

$$Q_L = A\frac{dx_0}{dt} + \frac{1}{2}.\left(\frac{v}{\beta} + K_e\right).\frac{dp_L}{dt} \quad , \qquad (2)$$

where y_1 is cylinder position, K_e structural stiffness, v pressurised hydraulic oil volume, β bulk modulus of hydraulic oil.

Load model of the system include quarter car model and cylinder mass. Also, dynamic equation can be written as

$$m_0\ddot{x}_0 = f(t) + k_1(x_1 - x_0) - b_0\dot{x}_0 \qquad (3)$$

$$m_1\ddot{x}_1 = k_1(x_0 - x_1) - k_2(x_1 - x_2) - b(\dot{x}_1 - \dot{x}_2) \qquad (4)$$

$$m_2\ddot{x}_2 = k_2(x_1 - x_2) + b(\dot{x}_1 - \dot{x}_2) \qquad (5)$$

where m_0 , m_1 and m_2 are piston, axle and quarter-car masses. b and k are viscous friction and stiffness coefficients of the same indices of mass.

It is clear, that hydraulically controlled road simulator has nonlinear characteristic caused by valve orifices. Nonlinearity has square root characteristic related to load pressure. In figure 3 it seems a sample valve flow characteristic via changing load pressure.

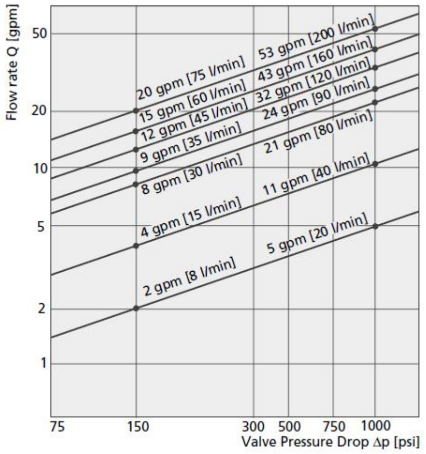

Figure 3. Load pressure vs. flow rate graph of a sample valve. [25]

Another nonlinear effect is caused by test specimen. Motorcycle suspension has nonlinear spring stiffness. Finally, these nonlinearities affect the control performance and should make effective linearization of the system model to have more accurate linear control performance.

3. CONTROL STRATEGY

The system wanted to control is combination of hydraulic test system and test specimen and has highly nonlinear characteristic.

Test systems should have universal design, so that changing of the test specimen should not caused in putting out of use the test system. Most important part of universal design is control algorithm. Control approach should be able to compensate the effect of the test specimen changing. Tested component could be a chasis or a suspension. Because of this reason, a system identification procedure is necessary.

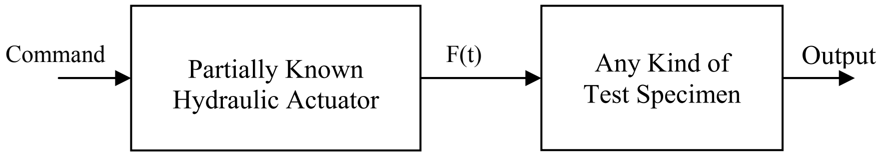

Figure 4. Modelling situation of the test systems.

Analytically control rule selection and optimal control signals synthesis are not simple processes due to complexity of the system. Iterative learning control is suitable approach for tracking control. Control algorithm researches optimal control signal subject to system capacity, noise characteristic, nonlinearities, saturations and uncertainties.
As a conclusion, model based iterative learning control is suitable road simulators/ test systems and detailed in subsections.

4. HYDRAULIC AXIS CONTROL

Road data is generally collected as acceleration and strain. Control approach has a cascade control scheme, inner and outer loop. Outer loop include model based iterative learning control and inner loop is real time axis control.

PID control could be used in this part of the control algorithm. PID performance could be improved by dynamic pressure feedback, which decreases damping of the system and increases stability of the system. To get the dynamic behaviour of load pressure a high pass filter should be used, related to [2, 26].

PID loop performance affect the performance of the completely control performance. To be able to simulate road, bandwidth of the PID loop should consist road data frequency spectrum. Increasing bandwidth (or rise time) can be caused in increasing resonance (or damping). To summarize, the optimal PID parameter changing by the application and road data specification and the solutions are subjective.

Disturbance feedforward usage increases the performance of PID. Feedback control is bounded by the stability, saturation and noise. Needed component, especially derivative, can be added by disturbance feedforward controller. Optimal feedforward controller can be designed by [27].

Consequently, completely inner loop, real time axis control, is showed in Figure 5.

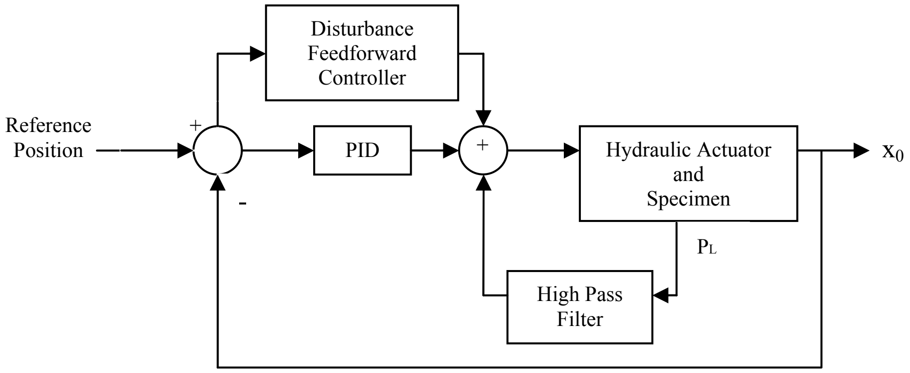

Figure 5. Hydraulic axis control.

5 .INVERSE SYSTEM IDENTIFICATION

System identification is an important part of the model based control algorithms. On the other hand system identification bring with modelling error and control effort problems. Also, designers should follow these steps; selecting identification procedure (linear or nonlinear, time domain or frequency domain), system identification and model validation.

5.1. System Identification

System identification procedure selection is an important part of the control algorithm. Model accuracy affects directly tracking performance.

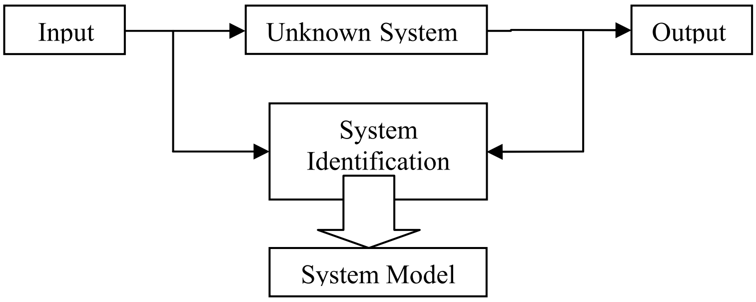

Figure 6. System identification.

In test systems, it must be considered that the system has complexity and nonlinearity. Nonlinear system identification needs static nonlinear component/function not only for hydraulic system but also for test specimen. Nonlinear system identification should be feasible for hydraulic system, however, test specimens have not standard nonlinearities, so that it is restrict with the universality. Test specimen can be a motorcycle or a tie rod end. To summarize, linear model identification is a feasible solution.

Time domain modelling directly uses difference equation, calculates the parameter of the equation, and the results are more realistic and applicable, detailed in [22]. Additionally time domain linear system identification Autoregressive Moving Average Model with exogenous inputs model (ARMAX) is selected, because of the noise model and moving average specification of ARMAX. Difference equation or polynomial structure of ARMAX is like in (6) and schematic display in Figure 7, like in [28].

$$y_k = \sum_{i=1}^{n} a_i y_{k-i} + \sum_{i=0}^{m} b_i u_{k-i} + \sum_{i=1}^{p} c_i e_{k-i} \qquad (6)$$

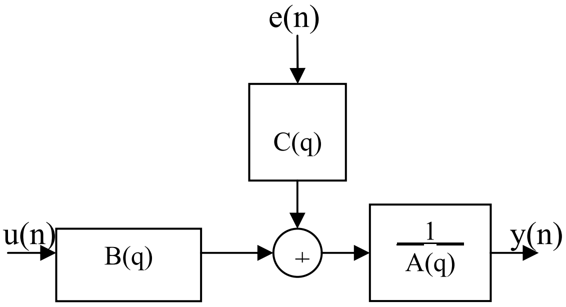

Figure 7. ARMAX model structure.

To improve quality of the modelling, using of wide range of frequency selection for reference signal so important, that estimation of a linear model for nonlinear system bring with modelling error and it can be minimized by getting finely averaged parameters. Additionally, white noise is used to improve the quality of modelling.

Validation procedure of the system model is showed in Figure 8 and mathematical expression is like in (7). If RMS error ratio - (14) shows calculation- is in accepted range of designer, then the model validation will completed.

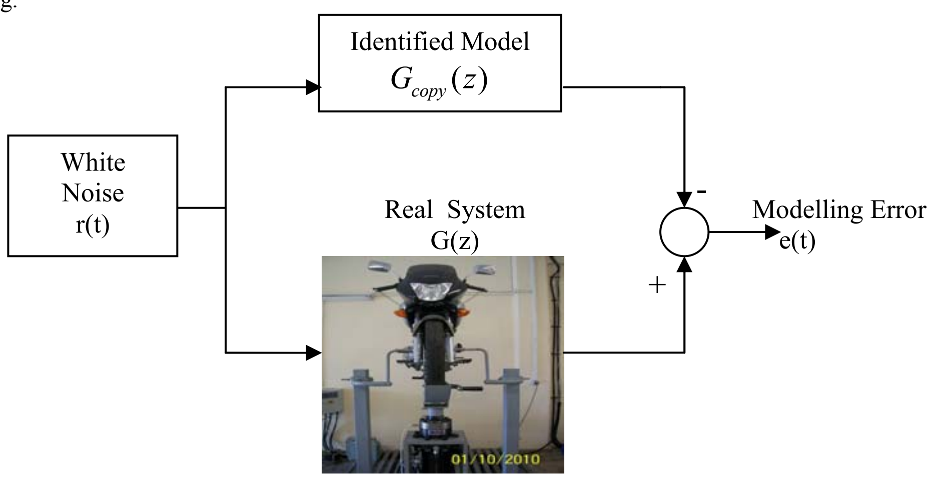

Figure 8. Model validation.

$$e(t) = r(t)\left(G(z) - G_{copy}(z)\right) \tag{7}$$

Finally, system identification procedure affect control performance, so it is important to have model with good approximation.

5.2. Synthesis of Inverse Model Controller

,

System Identification is a step to be able to get an inverse model controller. Theoretically, inverse model controller causes in absolutely tracking. However, there are basically some problems that non minimum phase model structure has not a stable and causal inverse model and inverted model (for minimum phase systems) can cause in saturation problem, explained in [29].

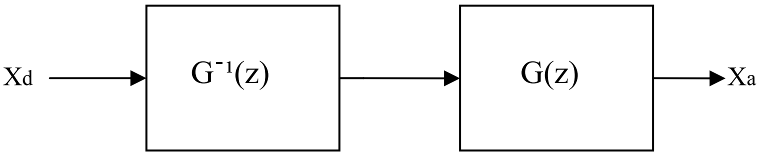

Figure 9. Basic inverse model control.

Zero Phase Error Tracking Algorithm (ZPETC) allows the designer getting more realistic solution, detailed in [30]. In (8) it seems symbolic discrete transfer function of the system.

$$G(z^{-1}) = \frac{y(k)}{y_d(k)} = \frac{B^a(z^{-1}).B^u(z^{-1})}{A\,(z^{-1})} \qquad (8)$$

In this equation; $B_c^a(z^{-1})$ is acceptable zeros (in the unit circle), $B_c^u(z^{-1})$ is unacceptable zeros (out the unit cycle), $A_c(z^{-1})$ is stable system poles, $y_d(k)$ is reference input and $y(k)$ is process variable. Using $B_c^u(z^{-1})$ as poles of the inverse model controller causes in instability. On the other hand, no using $B_c^u(z^{-1})$ causes phase problem. Finally, control rule of the control system is

$$u(k) = \frac{A\,(z^{-1}).B^{u*}(z^{-1})}{B^a(z^{-1}).[B^u(1)]^2}.y_d(k) \quad , \qquad (9)$$

and the inverse controller is

$$G^{-1}(z^{-1}) = \frac{A\,(z^{-1}).B^{u*}(z^{-1})}{B^a(z^{-1}).[B^u(1)]^2} \quad , \qquad (10)$$

where $B_c^{u*}(z^{-1})$ is zero phase part and u(k) is control signal.

$$B^u(z^{-1}) = b_0^u + b_1^u.z^{-1} + ... + b_n^u.z^{-n} \rightarrow B^{u*}(z^{-1}) = b_n^u + b_1^u.z^{-(n-1)} + ... + b_0^u.z^{-1} \qquad (11)$$

ZPETC is an effective solution; however, controller output could be still saturated. Therefore, a gain to realize the controller output should be used. In literature, there are different approaches to model inversion problem, [31] is another effective way. Consequently, completely inverse model control scheme of the controller is like in Figure 10.

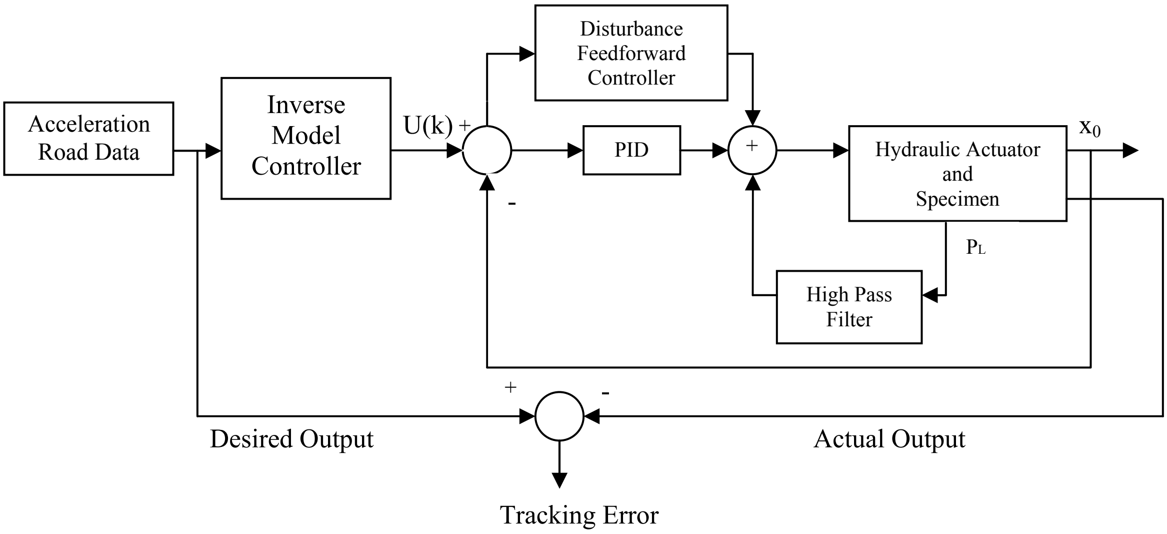

Figure 10. Inverse model control for ILC.

6. ITERATIVE LEARNING CONTROL

Iterative Learning Control (ILC) is a tracking control approach. It optimizes the controller output iteratively subjected to saturation and nonlinearity. Basic concept of ILC seems in Figure 11. ILC could be combined with different kind of control approach and detailed in [32].

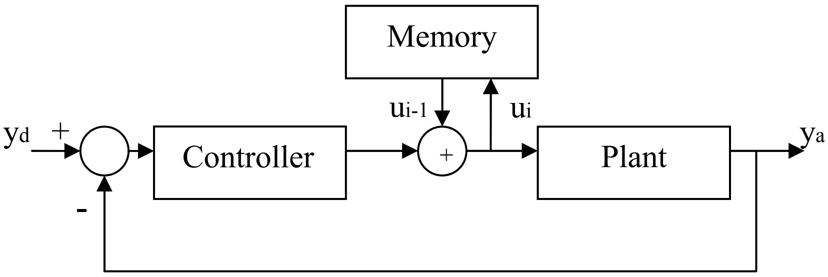

Figure 11. Basic ILC.

Firstly, inverse model controller is used and control signals and system outputs are recorded in the memory with sampling rate of the PID loop. The recorded file's mathematical description is like in (12).

$$\begin{aligned} u_0(k) &= y_d(k).G^{-1}(z) \\ e_0(k) &= y_0(k) - y_d(k) \end{aligned} \tag{12}$$

And then optimization procedure applied due to (13).

$$\begin{aligned} u_j(k) &= u_{j-1} + P.e_{j-1}(k).G^{-1}(z) \\ e_j(k) &= y_j(k) - y_d(k) \\ 0 &< P \le 1 \end{aligned} \tag{13}$$

In this equation P is weighting gain. Theoretically, high gain in the range of $0 < P \le 1$ provides high convergence speed. Noise and nonlinearity bound the convergence and could be cause divergence or oscillation. Also an optimum gain improves the stability with optimum convergence speed.

To calculate the performance of the control algorithm RMS error ratio is used as a statistical parameter,

$$RMS \quad Error \quad Ratio = \frac{RMS\left(e(k)\right)}{RMS\left(y_d(k)\right)} \quad . \tag{14}$$

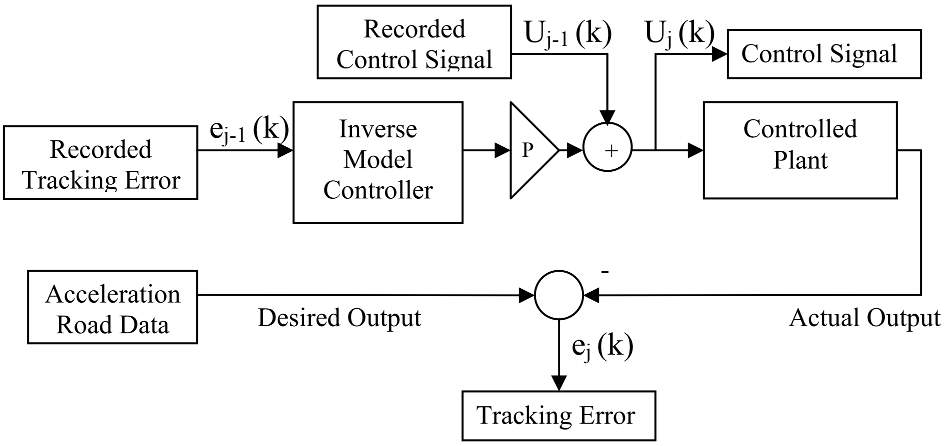

Figure 12. Model based ILC.

6.1. Experimental Results

Tracking control solution is described. As a test specimen motorcycle is used in road simulator. Road simulators have special mechanic, hydraulic and control hardware design. It seems road simulator in Figure 13.

Figure 13. Road simulator.

A desktop PC converted to real time controller and optimized codes are written in Labview. Real time axis control has 2 kHz loop frequency. By the time, sampling frequency of data acquisition card selected higher than control loop's frequency to be able to filter the signals by averaging.

Firstly, road data of the motorcycle is collected. An ICP type accelerometer is used and located to the axle of motorcycle. In road simulator, the same sensor and the same place are used for a reliable test.

Figure 14. Data collection from the axle.

After getting the road data, it is used as reference signal of the model-based ILC. Inner loop performance seems in Figure 15. PID loop allows tracking the reference signal with nearly zero error.

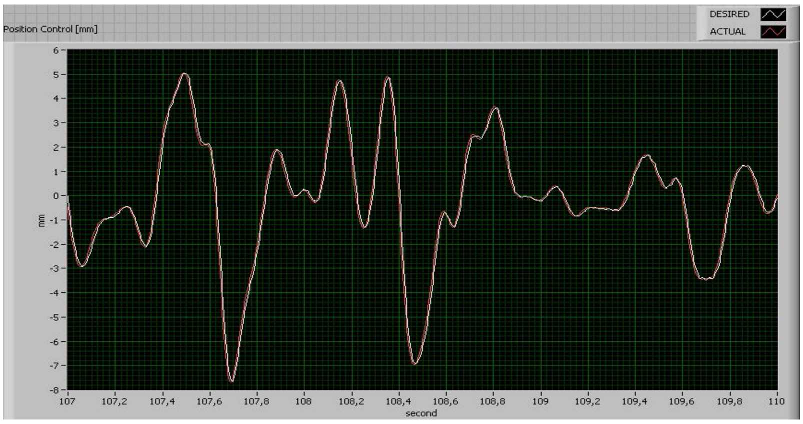

Figure 15. Hydraulic axis control results.

Acceleration control results after 42 iterations seem in Figure 16.

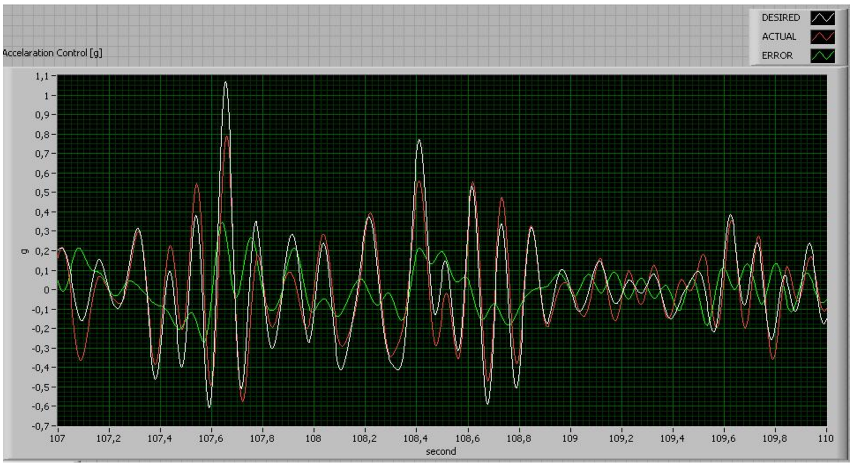

Figure 16. Acceleration control results after 42 iterations.

Finally, error ratio, between desired and actual data, is showed in Figure 17. It seems that RMS error ratio between desired and actual decreased by iteration increasing. Convergence speed is related road data quality, hydraulic capacity and linearity, electrical and mechanical noises.

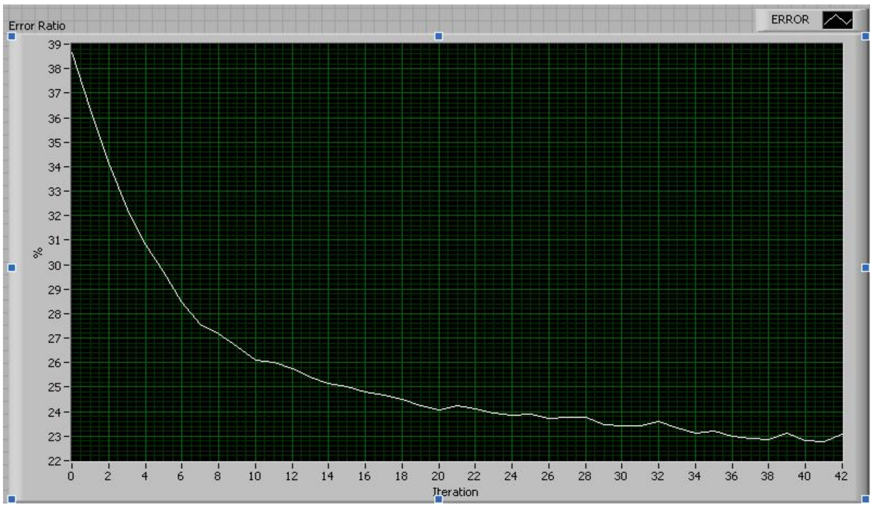

Figure 17. Error ratio vs. iteration.

7. CONCLUSION

Road simulators or test systems should have universal control structure and should be able to reproduce real forces on the test specimens. To solve the control problem, time domain model based ILC is designed and implemented. The results show, that simulation quality of the test system increasing by the iteration of the control algorithm. Most important advantages of the control approach are universality and guaranty for optimization.

The control approach has efficiency in control signal optimization; however, parameter changing of the system could be caused in error ratio increment during test. Additionally, there should be an adaptive algorithm combined with ILC to observe parameter changing if it is possible defining an universal rule.

System identification quality affects convergence speed and minimum error ratio. To get a better solution nonlinear modelling (universal, useful) could be used, as an applicable working [33], could be implemented to improve the performance.

A nonlinear control approach to linarize inner loop, improves the algorithm efficiency by the elimination of the nonlinearity effects. Feedback linearization or sliding mode control, as a nonlinear control approach, can be implemented to axis control, like in [34, 35].

Consequently, as a tracking control solution discrete time domain model- based iterative learning control approach is designed and implementation results are positive.

Acknowledgment:

This paper is a product of TÜBİTAK- TEYDEB Project (No: 7090370). Thanks for support of TÜBİTAK. "

REFERENCES

[1] Plummer, A. R. "Control Techniques for Structural Testing: a Review," ***Proc. IMechE, J. Systems and Control Engineering***, .221(I): 139-169 (2007).

[2] Tuncelli, A.C. Güner, H., Longchamp, R., " Hydraulic Axis Control Using Pressure Feedback", ***Proceeding of IEEE Int. Workshop on Intelligent Motion Control***, 20-22 August,663-668 (1990).

[3] Nguyen, Q.H., Ha, Q.P., Rye, D.C., Durrant-Whyte, H.F., "Force/Position Tracking for Electrohydraulic system of a Robotic Excavator," ***Proceedings of 39th IEEE Conference on Desicion and Control***, Australia, 5224-5229, (2000).

[4] A.O. Gizatullin, K. A. Edge, "Adaptive Control for a Multi-axis Hydraulic Test Rig,," ***Proc. IMechE, J. Systems and Control Engineering***, 221 (I):183-198 (2006).

[5] Clarke, D.W. Hinton, C. J. "Adaptive Control of Material-testing Machines," ***Automatica,*** 33(6):1119-1131 (1997).

[6] Stoten, D.P., Gómez, E.G., "Adaptive Control of shaking tables using the minimal synthesis algorithm"**,** ***Phil. Trans. R. Soc. Lond. A***, 359:1697-1723 (2001).

[7] Daley, S., "Application of a fast self-tuning control algorithm to a hydraulic test rig," ***Proc. IMechE,*** .201(C4):285-295 (1987).

[8] Widrow, B., Plett, G., "Adaptive inverse control based on linear and nonlinear adaptive filtering," ***in Proc. 1996 International Workshop on Neural Networks for Identification, Control, Robotics and Signal/Image Processing,*** Venice, Italy, 30–38(1996).

[9] Cunha, M.A.B., Guenther, R., De Pieri, E.R., "A fixed cascade controller with an adaptive dead-zone compensation scheme applied to a hydraulic actuator", ***Control 2004, Bath, United Kingdom,*** (2004).

[10] Zhidong Y., Qitao, H., Junwei, H., Hongren, L., "Adaptive Inverse Control of Random Vibration Based on The Filtered-X LMS Algorithm," ***Earthquake Engineering and Engineering Vibration,*** 9(1):141-146, (2010).

[11] De Cuyper, J. , Swevers, J., Verhaegen, M., Sas**,** P., "H∞ Feedback Control for Signal Tracking on a 4 Poster Test Rig in the Automotive Industry," ***proceedings of the ISMA*** 25: 61-68 (2000).

[12] De Cuyper, J., Verhaegenb, M., Swevers , J. "Off-line Feed-forward and H_∞ Feedback Control on a Vibration Rig," ***Control Engineering Practice,*** 11:129–140 (2003).

[13] Vaes, D., Engelen, K., Anthonis, J., Swevers, J., Sas, P.,"Multivariable feedback Design to Improve Tracking Performance on Tractor Vibration Test Rig," ***Mechanical Systems and Signal Processing,*** 211051-1075(2007).

[14] Wijnheijmer**,** F. P. "Modelling and Control of a Hydraulic Servo System H_∞ Control and LPV Control versus Classical Control," ***Master Thesis, University of Technology Eindhoven***, (2005).

[15] Smolders, K., Volckaert, M., Swevers, J., "Tracking Control of Nonlinear Lumped Mechanical Continuous-time Systems: A Model Based Iterative Learning Approach," ***Mechanical Systems and Signal Processing,*** 22.1896-1916, (2008).

[16] De Cuyper, J., Vaes, D., Dehandschutter, W., Swever, J., “ Experimental H_∞ Control to Improve an Industrial off-line Tracking Control Scheme on an Automotive Suspension Test Rig,” ***Proceeding of IEEE International Symposium on Computer Aided Control System Design***, U.K, 63-68 (2002).

[17] Daley, S., Hatönen , J., Owens, D.H., “Hydraulic Servo System Command Shaping Using Iterative Learning Control,” ***UKACC Conference, Control*** Bath, UK, (2004).

[18] De Cuyper, J., “Linear Feedback Control for Durability Test Rigs in the Automotive Industry,” Ph. D. Thesis***, Katholieke Universiteit Leuven,*** Belgium, (2006).

[19] Cherng, J.G., Göktan, A., French, M. Gu Y.,.Jacob A., “Improving Drive Files for Vehicle Road Simulations,” ***Mechanical Systems and Signal Processing,***15-1007-1022 (2001).

[20] De Cuyper, J., Coppens, D., Liefooghe, C., Swever, J., Verhaegen, M., “ Experimental H_∞ Control to Improve an Industrial off-line Tracking Control Scheme on an Automotive Suspension Test Rig,” ***Proceedings of IEEE International Symposium on Computer Aided Control System Design***, U.K,.63-68, (2002).

[21] Balkan, T., Konukseven, E. İ., Çalışkan, H., Dursun, U.,” A Control System for Vehicle Durability Test Rig,” ***Proceeding of the Automotive Tecnologies Congress*** 2010, Bursa, 2010.

[22] De Cuyper, J., Coppens, D., Liefooghe, C.,. Swevers, J., Verhaegen, M., “Advanced Drive File Development Methods for Improved Service Load Simulation on Multi Axial Durability Test Rigs,” ***Proc. of the International Acoustics and Vibration Asia Conference,*** Singapore, 339-354, (1998).

[23] Ercan, Y. “Akışkan Gücü Kontrolü Teorisi”, ***Gazi Üniversitesi Yayınlar***ı, (1995).

[24] Çalışkan, H., “Modelling and Experimental Evaluation of Variable Speed Pump and Valve Controlled Hydraulic Servo Drives,” ***Master Thesis, Middle East Technical University,*** (2009).

[25] Datasheet of MOOG D661 series valves.

[26] W.J. Thayer, “Transfer Functions for MOOG Servovalves,” ***Inc., East Aurora,*** New York, (1958).

[27] I.E. Köse , C.W. Scherer, “Robust L2-gain Feedforward Control of Uncertain Systems Using Dynamic IQCs”, ***Int. J. Robust and Nonlinear Control,*** 19:1224-1247,(2009).

[28] Ljung, L. “System Identification- Theory for The User,*”* 2nd ***ed., PTR Prentice Hall,*** Upper Saddle River, N.J., (1999).

[29] Kuo*, B.C. “*Automatic *Control Systems***,”** 5th ed. , ***Prentice-Hall***, (1987).

[30] Tomizuka, M., ”Zero Phase Error Tracking Algorithm for Digital Control,” ***J. Dynamic Systems, Measurement and Control,*** 109:65-68, (1987).

[31] K. George, M. Verhaegen, J.M.A. Scherpen, “A systematic and Numerically Efficient Procedure for Stable Dynamic Model Inversion of LTI Systems,” ***In Proceedings of the 38th IEEE Conference on Decision and* Control**, 1881–1886, (1999).

[32] Vervoerd, M.H.A., “Iterative Learning Control- A Critical Review,” ***Ph. D. Thesis, University of Twente,*** (2005).

[33] . Dzielinski, A “Neural Network-based Narx Models in Non-linear Adaptive Control,” I***n Proceedings of the Int. J. Appl. Math. Comput. Sci. ,*** 12(2): 235–240,(2002).

[34] Vossoughi, G., Donath, M., “Dynamic feedback linearization for electrohydraulically actuated control systems,” ***ASME J. Dynamic Systems, Measurement and Control,*** 117: 469-447, (1995).

[35] Q.P. Ha, Q.H. Nguyen, D.C. Rye, H.F. Durrant-Whyte, "Sliding mode control with fuzzy tuning for an electro-hydraulic position servo system," ***Proc. of the IEEE Int. Conf. On Knowledge-based Intelligent Electronic Systems (KES 98),*** Adelaide Australia, 1: 141-148, (1998).